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NUMERICAL COUPLING BETWEEN DAMAGE AND GAS PERMEABILITY FOR CONCRETE APPLIED ON A 3D SPLITTING TEST

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Abstract. Due to the industrial needs, one of the key issues nowadays is to develop numerical tools that are able to predict the leakage rate through a cracked structure. This paper presents a validation of a numerical modelling of leakage rate through a mortar specimen in a splitting test versus experimental results. The mechanical state of the material is described by means of an enhanced non-local damage model which takes into account the stress state and provides a realistic damage field at failure. Two continuous approaches based on permeability-damage law are considered to study the coupling between the mechanical state of the material and the permeability. The first one lies on coupling the permeability of a crack with the mechanical state by means of the damage variable, and the second one is based on the regularized equivalent strain. Results show that the first approach isn't acceptable in case of discontinuous macrocracking while the second one predict well the permeability in the same case.

1 INTRODUCTION

During their service life, due to external loading (mechanical and/or environmental), concrete structures may undergo damage in a diffuse manner (microcracking) at the material scale and/or localised (macrocracking) at the structural level. The estimation of the evolution of transfer properties in such a cracked material is a key issue for structural durability analysis. Choinska et al. **[1]** observed in their experimental study three different regimes of permeability evolution. A first regime exhibiting relatively a slight permeability increase, which is due to the presence of microcracks spread out in the material. Coupling between permeability and microcracking (diffuse damage), has been proposed by Picandet et al. **[2]** when the material is in compression. A second regime is also observed where the permeability of the material increase rapidly due to strain localization. This regime is an intermediate phase between diffuse damage and discontinuous macrocracking. A third regime is observed where macrocracks are formed and permeability is governed at the macrostructural level by Poiseuille's law and mainly depends on the crack opening, this regime is characterized by a slower rate of permeability increase with respect to the second regime.

Two approaches are considered in order to numerically simulate the coupling between the mechanical state of the material and the permeability:

- A first approach was proposed by Pijaudier-Cabot et al. **[3]** that is based on a permeability-damage law, which is a combination of Picandet and Poiseuille's permeability. Where the two permeabilites are directly related to damage.

- A second approach proposed in this paper that is also based on a permeability-damage law, Picandet's permeability is retained but Poiseuille's permeability is no longer function of damage but related to the regularized equivalent strain.

Those two approaches allow to predict a leakage rate without need to calculate the CODs. The permeability is obtained at each integration point and is used to compute the leakage rate point wise in the volume. The mechanical state of the material is described by means of an enhanced non-local damage model which takes into account the stress state and provides a very realistic damage field representing micro cracking and macro cracking at failure **[4]**.

A physical experiment has been performed on a mortar specimen subjected to splitting test; the gas permeability of the specimen is measured during the test at different load levels. The validation of the approach against experimental results is performed on the leakage rate perpendicular to the disk for different load stages.

The physical experiment of the splitting test will be detailed in section 2 and the numerical models (damage and continuous approach for leakage rate) will be presented in the section 3. In section 4 the application of the numerical models on the splitting test will be detailed.

2 PHYSICAL EXPERIMENT

The experiment **[5]** consists of performing a brazilian splitting test applied on mortar specimens. The Brazilian splitting test is an indirect tension test used to measure tensile strength of concrete, rocks and other geomaterials. It consists of loading a cylindrical specimen along a diametral plane by means of steel or wood bearing plates, as shown in **Fig.1**. Gas flow rate measurements are taken after partially unloading the sample to avoid brutal rupture (See **Fig. 2**). The sample has a cylindrical shape of 40 mm of height and 110 mm of diameter. It is worth noting that the sample wasn't a perfect cylinder, a difference of 0.1 mm in diameter was observed. The Young modulus is equal to 18 MPa and the Poisson's coefficient equal to 0.2.

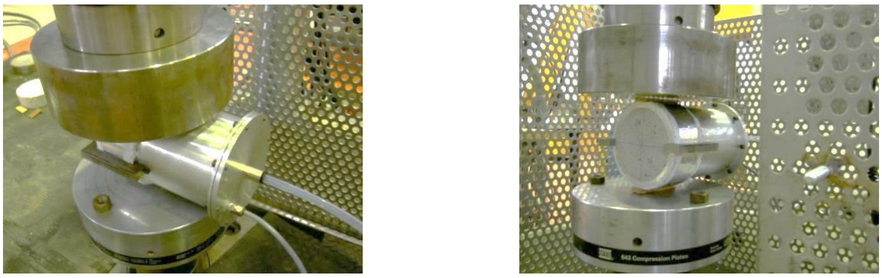


Figure1: Permeability analysis while performing a Brazilian test on a mortar sample. **[5]**

The splitting test is controlled and directed by the crack opening located on the horizontal transversal line of the bigger face of the specimen, a displacement sensor is placed in the central part of this face to do the controlling. The other face (the smaller) is discretized by means of a speckle pattern in order to perform Digital Image Correlation and get the 2D displacement field on the surface.

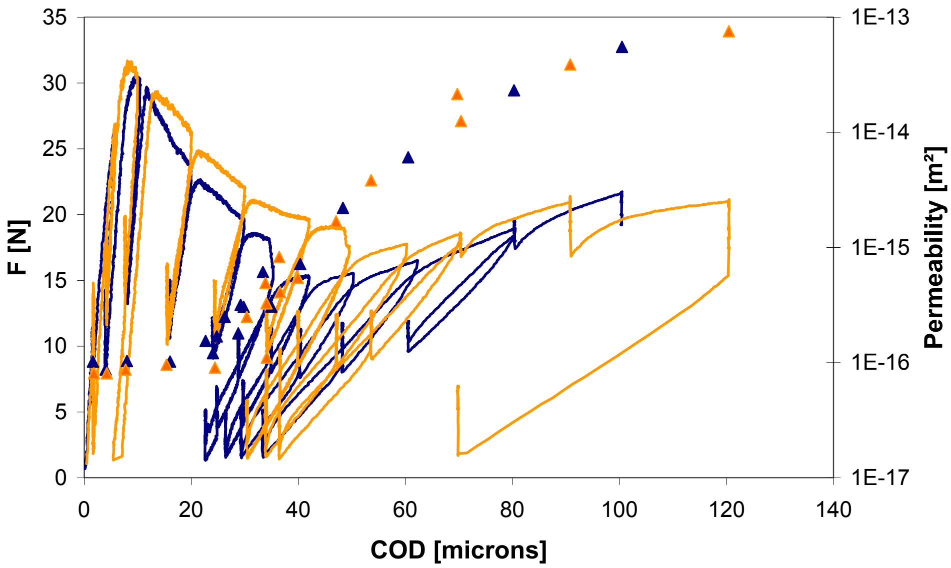


Figure2: Mechanical behavior and permeability evolution versus the crack opening displacement for two mortar specimens. **[5]**

The Mechanical response and the permeability evolution of two mortar specimens are given in **Fig**. 2. The mechanical response is composed of an elastic part, and after reaching the peak the softening behavior ends by a complete split of the specimen. At COD equal to approximately 34 microns the specimen is split and the behavior afterwards is described by the half portion of the specimen subjected to compression loading. An analysis has proven that there was a 3D effect on the force-COD behavior of the specimen. The crack is initiated and propagated firstly on the bigger face and then is propagated in the longitudinal direction to reach the smaller face and propagate on it until the total split of the specimen. Therefore 3D simulations are needed.

The permeability evolution can be described by the three regimes proposed by Choinska: For crack openings varying from 0 to 30 microns a slight increase in the permeability is recorded which corresponds to the first regime. Afterwards the second regime appears when a large increase in the permeability begins for crack openings higher than 30 microns. Finally, one can see a decrease of the rate permeability increase. In the third regime, a coefficient ξ that includes the roughness of crack, the turtuosity and the constrictivity of the material is calculated at COD equal to 100 microns. This coefficient is an adjustment factor for the Poiseuille's law (See **Fig. 3**).

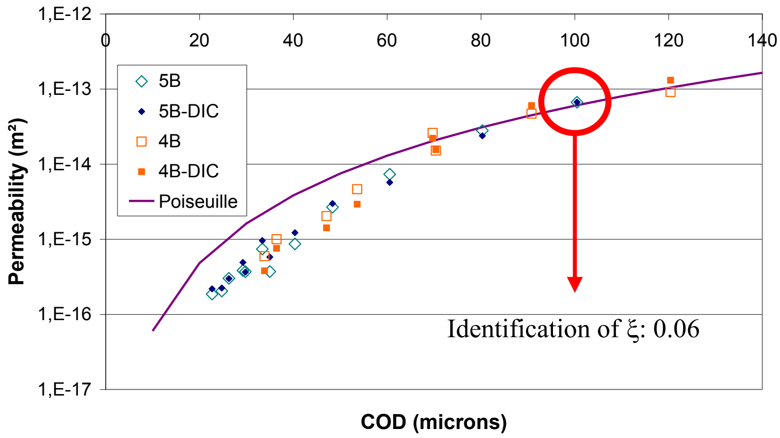


Figure3: Identification of an average roughness coefficient at COD equal to 100 microns. **[5]**

3 CONTINUOUS APPROACH BASED ON DAMAGE

The advanced numerical modelling of cracking in reinforced concrete structures may be dealt with either by means of advanced discontinuous models (G-FEM, etc.) or using continuous constitutive models such as damage mechanics. In this approach damage models are considered since the permeability-mechanical state coupling is based on damage. The enhanced non-local damage model that is based on the stress state will be reviewed in the following. In the second subsection the continuous approach is presented.

3.1 Regularized damage models

The loss of stiffness associated to mechanical degradation of the material is represented by D:

$$\sigma = (1 - D)C : \varepsilon \tag{1}$$

Where σ and ε are respectively the Cauchy stress tensor and the small strain tensor, and C is the tensor of elastic moduli.The parameter D range between 0 for virgin materials and 1 for completely damaged materials. It is assumed that D depends on a state variable Y, which in turn depends on the strains, Y = Y (ε).The basic idea of nonlocal damage models is averaging the state variable Y in the neighborhood for each point. In this manner, the nonlocal state variable $\tilde{Y}$is obtained:

$$\tilde{Y} = \int_v \alpha(d) Y dV / \int_v \alpha(d) dV \tag{2}$$

The weight function α depends on the distance d to the point under consideration. Generally a Gaussian function is used:

$$\alpha(d) = \exp[-\left(\frac{2d}{l_{c0}}\right)^2] \tag{3}$$

Where l_{c0} is a material parameter of the nonlocal damage model called characteristic length, and Y is the state variable, that drives the damage (D=D($\tilde{Y}$)) according to Mazars law:

$$Y = \sqrt{\sum_i [\max(0, \varepsilon_i)]^2} \tag{4}$$

Damage evolution follow a law which distinguishes tensile damage D_t and compressive damage D_c:

$$D = \alpha_t D_t + \alpha_c D_c \tag{5}$$

Where α_t and α_c are the weights computed from the strain tensor. The tensile damage D_t and compressive damage D_c are calculated as follows:

$$D_{t,c} = 1 - \frac{Y_{D0}(1 - A_{t,c})}{Y} - \frac{A_{t,c}}{e^{[B_{t,c}(Y - Y_{D0})]}} \tag{6}$$

The newly version of this damage model, the non local stress based (**NLSB**) is characterized by the regularization that takes into account the stress state of the material. A modification on the Gaussian function is applied and the function becomes:

$$\alpha(d) = \exp[-\left(\frac{2d}{l_{c0} * \rho}\right)^2 \;] \tag{7}$$

Where ρ a factor that is calculated for each point and depends on the principal stresses of the medium.

3.2 Permeability-Continuous approach

The continuous approach is based on a permeability-damage law that is presumed to describe the three different regimes. The following equation is one of the matching laws proposed by Pijaudier-Cabot et al. which was proven to be the most convenient to describe the permeability evolution.

$$\log(k) = (1 - D)\log(k_D) + D\log(k_f) \tag{8}$$

This law is a logarithmic combination of Picandet's permeability for diffuse damage (low damage) and Poiseuille's permeability when a macrocrack is formed. k_D and k_f are two local permeabilites defined for each integration point in the medium and D is the value of damage at the integration point. Regarding diffuse damage, the first term of the modified Picandet's permeability is retained. Hence k_D is equal to:

$$k_D = k_0\left[1 + (\alpha D)^\beta\right] \tag{9}$$

Where α and β are two parameters to be determined from experimental results. They were fitted by Picandet to 11.3 and 1.64 respectively on experimental results of axial compressive damage on gas permeability of ordinary and high-performance concrete. However for a splitting test the damage is mainly generated in tension and is localized in the crack surface,

Consequently a negligible variation of the mean structural permeability due to diffuse damage is seen in the physical experiment.
Concerning the permeability of a macrocrack, Poiseuille's permeability of two parallel planes ($k_P = \xi\frac{[u]^2}{12}$) is considered with taken into account the coefficient (ξ). Pijaudier-Cabot et al. supposed equivalence at failure between continuous damaged domain with a damaged zone of width λl_c and discrete macrocracked domain with a crack opening $[u]$. This assumption was followed in order to substitute crack opening by damage field. Then the Poiseuille's permeability is equal to:

$$k_P = \xi \frac{(\lambda l_c)^2}{12}\left(F^{-1}(D) - Y_{D0}\right)^2 \tag{10}$$

Where l_c is the characteristic length, λ is a unit less factor that influences the width of the damaged band given equal to 2 and Y_{D0} is the damage threshold. The inverse damage evolution law $F^{-1}(D)$, based on equation (6), is used in order to represent the permeability k_f:

$$F^{-1}(D) = Y_{D0} - \frac{\ln(1-D)}{B_t} \tag{11}$$

The second approach consists firstly of using a function $F(\tilde{Y})$ instead of the inverse function of damage. Then the crack opening is related to this function as follows:

$$[u] = Dens * (F(\tilde{Y}) - Y_{D0}) \tag{12}$$

Where Y_{D0} is the threshold of damage (See **Table 1**) and *Dens* is an average of the density of the mesh of the fracture zone. $F(\tilde{Y})$ for a cracked element is the component of the regularized equivalent strain $\tilde{Y}$ for this element that is in the orthogonal direction to the element surface. That means that before applying **Eq. 12** the cracked elements and its orientations has to be identified using numerical tools such as the global tracking algorithm **[6]**. In case of splitting test, for sake of simplicity one can suppose that the plane of symmetry is the surface of the crack, it means all the elements of this surface are cracked and the orthogonal direction to the elements in this case is the horizontal direction parallel to the x axis. Thus, in this case $F(\tilde{Y})$ is the horizontal component of the regularized equivalent strain $\tilde{Y}$.
The permeability of a cracked element at the integration point k_f is defined as follows:

$$k_f = k_P \frac{[u].L}{S} \tag{13}$$

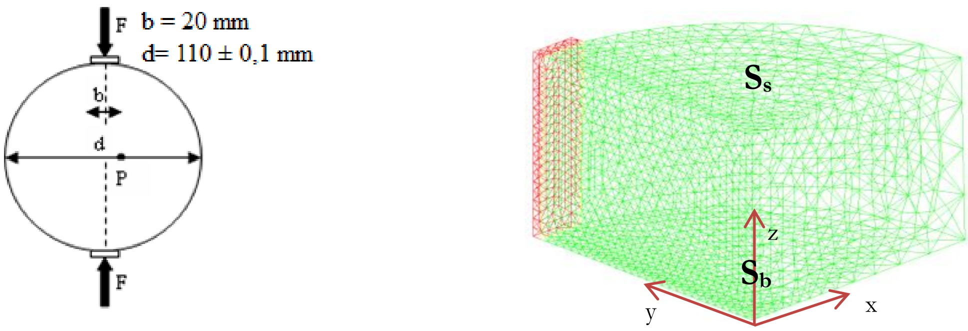
Where $[u]$ the crack opening of the element, and $\frac{L}{S}$ is the fraction between the length of the element and its surface. For sake of simplicity $\frac{L}{S}$ is calculated as $\frac{1}{l_e}$ where l_e equal to $3\sqrt{V_e}$, (V_e is the volume of the element).Thus k_f is equal to:

$$k_f = \xi \frac{[u]^3}{12 l_e} \tag{14}$$

To determine the total leakage rate, the permeability problem by imposing a pressure gradient has to be solved. Once the leakage rate is determined, by means of Darcy's law, the mean structural permeability can be calculated and will be compared to the permeability measured experimentally.

4 APPLICATION ON A 3D SPLITTING TEST

This numerical study is a simulation of the physical experiment presented in **section 2**. The steel bearing plates are modelled as rigid plates, with high Young's modulus (E = 300 GPa) and Poisson's ratio ν of mortar (ν=0.2) in order to avoid a confinement effect of mortar. Numerical simulations are performed in the FE code *Cast3m* with 4-nodes tetrahedral elements in 3D. Due to the symmetry of the problem, the computation domain consists of only quarter of the specimen. The mesh is shown in **Fig. 4** (b). It should be noted that the mesh is generated with the same conicity of the real specimen in order to reproduce the 3D effect in the simulations. **S_s** and **S_b** corresponds respectively to the smaller and bigger edge surfaces of the specimen. The post-peak behavior in splitting test includes a snap-back in the force displacement curve and therefore an arc-length control (by maximum strain or crack opening) is required to solve the numerical problem **[7,8]**.



(a) (b)

Figure 4: Brazilian splitting test (a) problem statement (b) 3D conic FE mesh.

4.1 Mechanical description

In this subsection the mechanical description by the stress based non local **NLSB** is concerned. Young's Modulus and Poisson's ratio of the mortar are taken from physical experiment. A calibration of the parameters is done for the model after finding a good numerical description of the physical response and the set of Mazars' parameters is given in table 1.

Parameter	NLSB
Y_{D0}	$3.5.10^{-4}$
A_c	1.4
A_t	0.88
A_c	800
A_t	4050
β	1.06
l_{c0}	7.5 mm

Table 1:Set of Mazars' parameters for the damage models

The point P on which the crack opening displacement is calculated is located on the central horizontal line of the bigger face distant of 10 mm from the center (See **Fig. 4** (a)). The numerical simulation of the mechanical response (Force versus COD at P) of the physical experiment presented in **section 2** is given in **Fig. 5.** This result shows that the stress based non local model NLSB is in a good agreement with the physical response in describing the behavior even after the total split. However, the model is elasto-damageable model that do not take into account the plastic deformation therefore the exaggerated snap-back where COD decreases from about 35 to about 30.5 microns is probably due to elastic discharge of the face where the COD of P is calculated. This drawback in the model will eventually affect the coupling since the permeability is directly linked to the mechanical state.

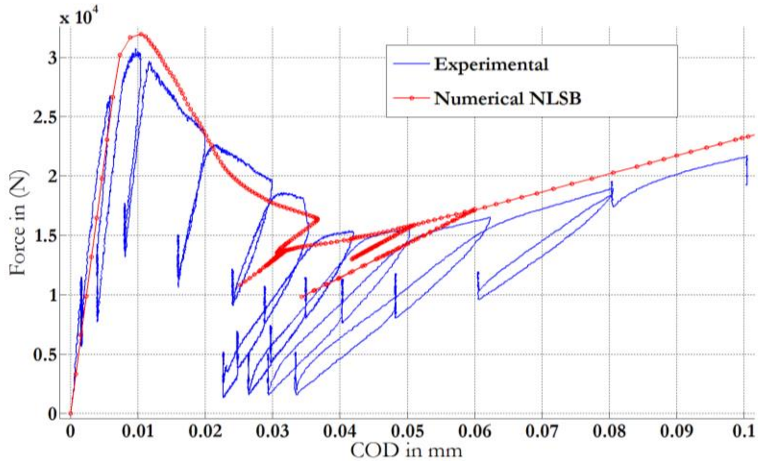


Figure 5: Mechanical response (Force versus COD) described by NLSB compared to experimental response.

4.2 Damage propagation

Damage fields at 4 loading levels given by the NLSB model are displayed in **Fig. 6**. At the peak A, damage is initiated in the center of the surface $\mathbf{S_b}$ and diffused in the volume. In the post-peak behavior (between A and B) localized damage propagates from the center on the surface $\mathbf{S_b}$ and in the transversal direction toward the surface $\mathbf{S_s}$. At point B the damage arrives to the surface $\mathbf{S_s}$ and between the points B and C damage propagates on the surface $\mathbf{S_s}$. At point C the behavior becomes the one of the half portion and almost all the crack surface is totally damaged. D corresponds to a total split with COD on P equal to 105 microns.

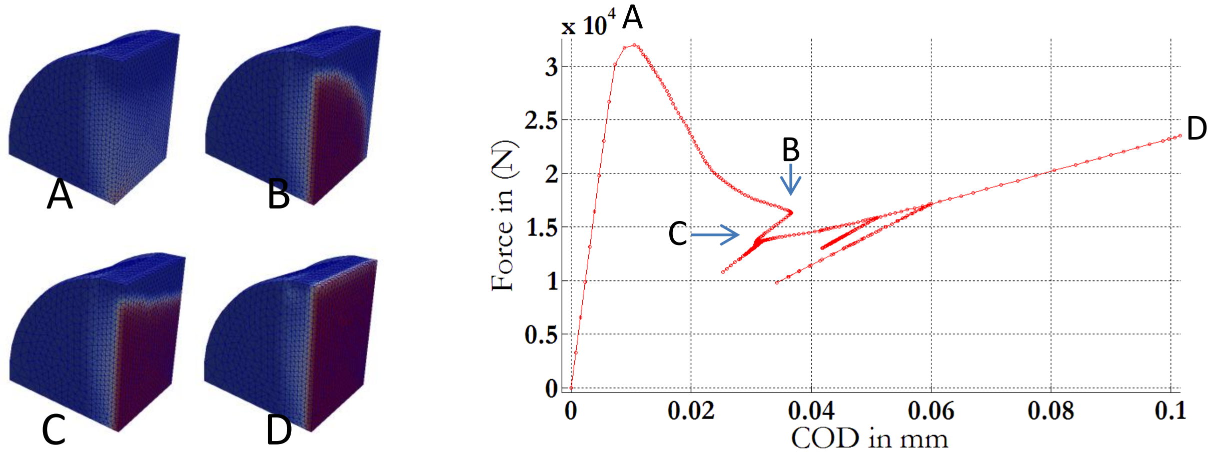


Figure 6: Damage fields given by NLSB at 4 loading levels A B C and D.

5 COUPLING PERMEABILITY-DAMAGE

Once the numerical simulation of the mechanical response is achieved, one can apply the matching law in the post treatment phase in order to obtain the permeability at each integration point and then compute the leakage rate point wise in the volume by applying a pressure gradient and solving the permeability problem (See **Fig. 7**). Hence, the mean structural permeability is calculated using Darcy's law and compared to experimental measurements.

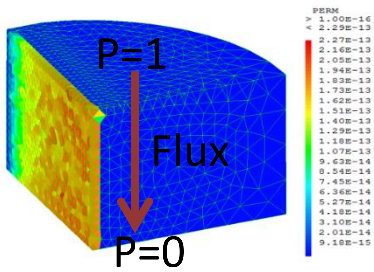


Figure 7: Solving the permeability problem by applying a pressure gradient.

The evolution of the mean permeability calculated by applying the matching law proposed by Pijaudier-Cabot et al. versus the COD at point P is presented in **Fig. 8**. It is shown that the estimated mean permeability for low level of damage is acceptable. However in the intermediate zone the permeability is overestimated due to an overestimation of the crack opening (COD at P ranging from 380 to 600 microns). Moreover for higher COD, the evolution of the mean permeability becomes asymptotic. This is due to the stabilization of the damage around 0.99. Consequently the relation between the crack opening and the inverse function of D $F^{-1}(D)$ (Eq. 11) could be discussed. Another limit is that for this model the damage state do not evolves during unloading. One can see on **Fig. 8** that during unloading a constant permeability is predicted.

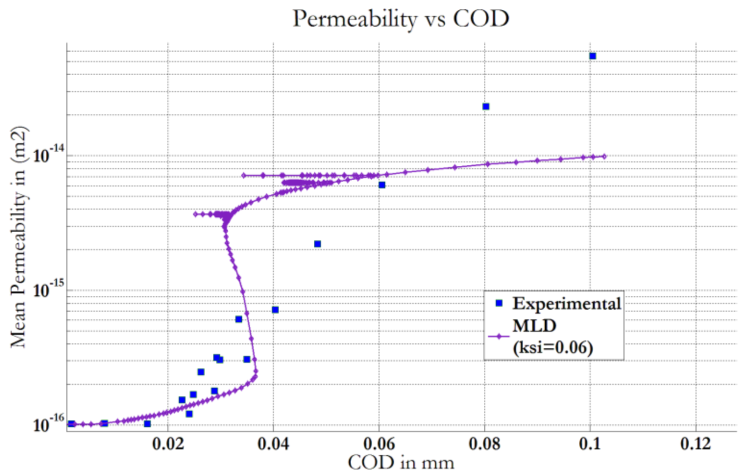


Figure 8: Mean permeability calculated by applying Matching law based on the first approach versus COD of point P.

The evolution of the mean permeability calculated by the proposed method as well as a comparison between the result of the two approaches are presented in **Fig. 9**. The coefficient ξ is supposed to be constant for any COD and is taken as calculated from the physical experiment at COD=0.1 mm equal to 0.06. This result shows that the mean permeability is very well predicted at the COD=0.1 mm where the coefficient ξ were calculated, however it is overestimated for lower CODs. The issue of constant permeability when unloading is resolved since the equivalent strain decreases and unlike the damage the equivalent strain do not stabilize but continue to increase with the crack opening.

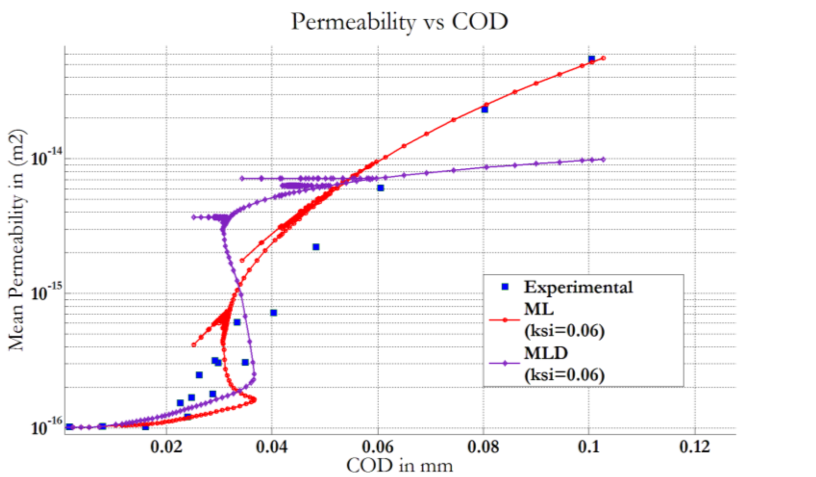


Figure 9: Mean permeability calculated by applying Matching law based on Damage MLD and by the proposed one based on equivalent strains ML versus COD of point P.

6 CONCLUSIONS

The mechanical simulation of the physical experiment of a splitting test performed on a mortar specimen were done using the NLSB model. Two approaches were considered in order to do the permeability-mechanical state coupling. A first approach that was proposed by Pijaudier-Cabot et al that is based on damage. The second one proposed in this article based on the regularized equivalent strain. The study has shown that the crack opening of an element cannot be directly related to its damage because the damage stabilize around 0.99 and do not evolves during unloading. It has been shown also that the crack opening can be related to the regularized equivalent strain since the prediction of the structural permeability using this approach is good compared to the experimental measurements.

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